

Seismic performance and effect of curved geometry on isolation system in horizontally curved bridge

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ABSTRACT

Seismic response of horizontally curved concrete box girder bridge isolated by the Elastomeric Rubber Bearings (ERBs) is carried out. The effect of curved geometry on the performance of isolation system is studied under excitation with four different ground motions of different frequency spectrum characteristic, and each ground motion contains three-directions. The selected bridge consists of three span continuous concrete box girder superstructure supported on piers and abutments. In the modeling of the bridge, the deck is modeled as a single spine beam, made up of small straight beam elements with 6 DOF at each node. The coupled equations of motion for isolated system are derived and solved in the incremental form using Newmark's step-by-step method. In addition, comparison is made between the response of curved isolated bridge with straight isolated bridge (having the same cross section and material property) in order to study the effect of curved geometry on the response of the isolation system. It is observed that ERBs system is effective for controlling the seismic response of curved bridge and effect of curved geometry makes no significant difference in peak response of ERBs system.

1. INTRODUCTION

In past various devastating earthquakes inflicted heavy damage to bridges resulting into heavy casualties and economic losses. It is observed that the damage to bridges in the earthquakes is mainly due to shear failure of piers and due to excessive displacement of bridge deck and bearings. Additionally, bridges with curved configurations may sustain severe damage owing to rotation of the superstructure or displacement toward the outside of the curve line during an severe earthquake (Galindo et al. 2009). Failure of bridges during a seismic event will seriously hamper the relief and rehabilitation work, as they serve as major access and evacuation routes during and after catastrophic events, so bridges come under the category of lifeline structures. Therefore, there is a need of finding more rational and substantiated solutions for protection of bridges from severe earthquake ground motion.

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The traditional way to improve performance of bridge during earthquake by reducing vibration due to seismic event is done by making its member stronger and more ductile. This approach, based on ensuring of strength-ductility combination, provides the strong seismic action as ultimate loads, accepting a certain number of structural or non-structural degradations. This indicates that, bridges designed with traditional methods are still vulnerable in strong seismic event. The performance of bridges during earthquakes can be improved by making use of suitable energy dissipation devices in the bridge system. In the case of bridges, those usually have a simple structural configuration, made from a continuous deck supported on the top of the pier by simple bearings only with the function of supporting gravity loads, the seismic isolation bearings, can be replace conventional bridge bearings, decouple the superstructure from piers and abutments during earthquakes. This significantly reduces the seismic forces induced in the bridge structure, and lowers the strength and ductility demands on the bridge (Kunde and Jangid 2003).

Lei and Chien (2004) shown that the isolation performance on base shear reduction of curved bridge will be closely related to the content of the earthquake and the curvature angle of the structure. They concluded that the use of the isolator with smaller stiffness in lead rubber bearing series or with lower frictional coefficient in the friction pendulum system series would induce a better performance on base shear reduction. Liu et al. (2011) established the three-dimensional computational model of a double-pier curved continuous girder bridge and viscous dampers were added at the positions of sliding bearings by them. Ates and Constantinou (2011a, b) studied the effects of the earthquake ground motions on the seismic response of isolated and non-isolated curved bridges including soil–structure interaction using response history analysis and response spectrum analysis. The above review indicates that very few studies are reported on the behavior of isolated horizontally curved concrete box girder bridge. Therefore, it will be interesting to study the dynamic behavior of isolated curved concrete box girder bridge and effect of curved geometry on the performance of isolation system.

The present study signifies the seismic response of horizontally curved concrete box girder bridge isolated by the ERBs system. Parametric study of ERBs is carried out for obtaining better response under different earthquake ground motion. Using different evaluation criteria effectiveness of ERBs is studied. Also, the effect of curved geometry on the performance of ERBs system is studied by comparing the response of curved isolated bridge with the response of straight isolated bridge.

2. MODELLING OF CURVED BRIDGE

The bridge model used for the present study is that of Federal Highway Administration Seismic Design Course, Design Example No. 6, prepared by BERGER/ABAM Engineers (Berger / Abam Engineers 1996), and also used by (Ates and Constantinou 2011a and b) for getting seismic response of isolated curved bridge with some modification. The selected bridge is three spans, cast-in-place concrete box girder superstructure supported on reinforced concrete columns as shown in Fig. 1. The span length of curved bridge along the centerline is 27.25 m, 33.5 m, and 27.25 m

respectively and width of deck is 11.8 m. The alignment of road way over the bridge is sharply horizontally curved (104°). The two intermediate bents consist of rectangular columns with cross section area 1.7 m^2 and 6.4 m height from ground surface. The super structure consists of three cell deck with 10% slope with horizontal. The geometry of the bridge and section properties is the same as in the original bridge in the FHWA example. It is presumed (without any checks) that the original bridge design is enough to sustain the loads and displacement demands when seismically isolated as described herein. The bridge is isolated with two isolators at each abutment and pier location for a total of eight isolators. The isolators are directly located above the cap of the rectangular columns and the abutments. The properties of the bridge deck and pier are as given in Table 1. The following assumptions are also made for seismic analyses of the bridges under consideration:

- 1) Bridge superstructure and piers are assumed to remain in the elastic state during the earthquake excitation,
- 2) The abutments of bridge are assumed as rigid and Piers are considered as fixed at ground level,
- 3) The effect of soil structure interaction is not taken in consideration,
- 4) The bridge deck is modeled as single spin beam made up from small straight beam element. Each adjacent element is connected by a node,
- 5) The mass of each element is assumed to be distributed between the two adjacent nodes in the form of point masses and,
- 6) Stiffness contribution of non-structural elements such as side walk and parapet is neglected.

The selected bridge is modeled as a multi degree of freedom (MDOF) system. Based on the detailed drawings of the curved bridge, a 3D evaluation model is made in MATLAB. As the central angle of curved concrete bridge is between 12° and 46° between supports, the deck is modeled as single spine beam, which is made up from small straight beam element with included angle less than 3.5° as specified in American Association of State Highway and Transportation Officials (AASHTO),

Table 1. Properties of bridge deck and piers

Properties	Deck	Piers
Cross-sectional area (m^2)	6.238	1.7
Moment of Inertia (m^4)	2.7074	0.409416
Young's modulus of elasticity (m^2)	3.2×10^{10}	3.2×10^{10}
Mass Density (kg/m^3)	2.5×10^3	2.5×10^3
Length/height (m)	88	6.4

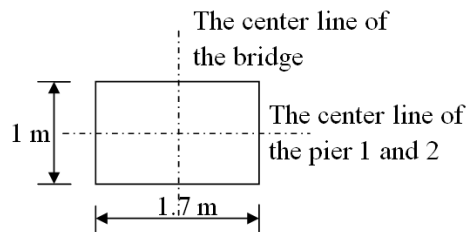
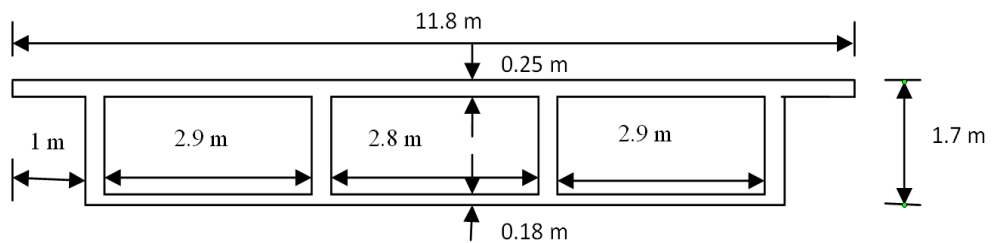
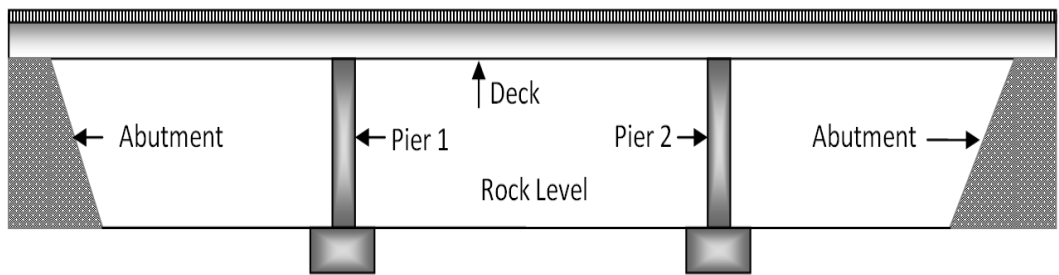
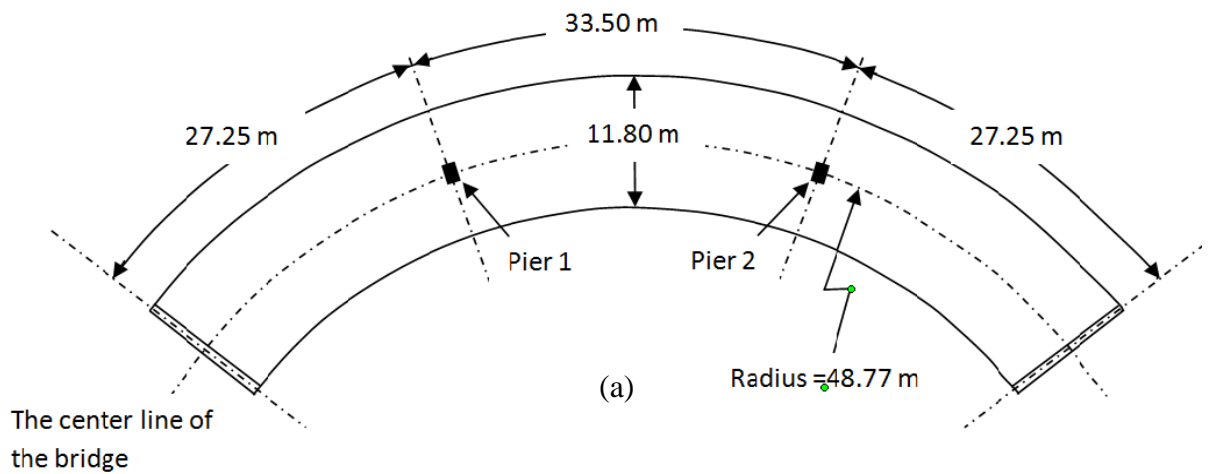


Fig. 1 a) The curved bridge plan, b) developed elevation, c) section of the superstructure, and d) horizontal sections of the pier.

load and Resistance Bridge design specification reported in National Cooperative Highway Research Program (NCHRP) report 620 (Redfield et al. 2008). The number of elements considered in the bridge deck and piers are 32 and 4, respectively. The idealized mathematical model of bridge is as shown in Fig.2.

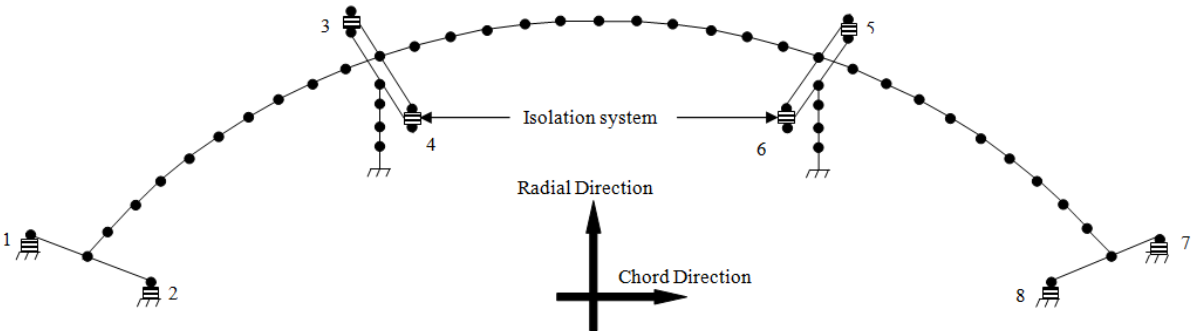


Fig. 2 Mathematical model of isolated bridge

3. GOVERNING EQUATIONS OF MOTION

The general equation of motion for a structural system subjected to seismic loads is express as

$$M\ddot{U}(t) + C\dot{U}(t) + KU(t) = -M\eta\ddot{U}_g(t) + bF(t) \tag{1}$$

where, $\ddot{U}(t)$ is the second time derivative of the displacement response vector $U(t)$, M , C and K are the mass, damping and stiffness matrices of the structure, $F(t)$ is the vector of control force inputs, $\ddot{U}_g(t)$ [m/s²] is the ground acceleration, η is a vector of zeros and ones, relating the ground acceleration to the bridge degrees of freedom (DOF), and b is a vector relating the force produced by the control device to the bridge DOFs.

Firstly, individual elemental stiffness matrix of each element is formed and using transformation matrix it converted in to global matrix. Global Stiffness matrix of structure is assembled using elemental global stiffness matrices. Similarly, global mass matrix for structure is assembled. Thus, response of the structure is evaluated step-by-step at successive increments of time. It is assumed that the properties of the system remain constant during the time increment. Incremental equations of motion are solved using the Newmark-beta method. The global damping matrix C is a combination of the distributed 5% inherent Rayleigh damping in the first two modes.

4. ELASTOMERIC RUBBER BEARING (ERBs)

ERBs consist of thin layers of rubber and steel plates built in alternate layers as shown in Fig. 3(a). The internal steel plates, referred to as shims. The vertical stiffness of the bearing is several hundred times the horizontal stiffness, which is due to the presence

of internal steel shims and horizontal stiffness of the bearing is controlled by the low shear modulus of elastomer. The steel shims also prevent the bulging of rubber. The damping in the bearing is increased by adding extra-fine carbon black, oils or resins and other proprietary fillers (Naeim and Kelly 1999). The dominant features of ERBs system are the parallel action of linear spring and viscous damping. Schematic diagram of the ERBs system is shown in Fig. 3(b), which represents the linear behavior with viscous damping. The restoring force developed in the bearing, F_b is given by

$$F_b = c_b \dot{x}_b + k_b x_b \tag{2}$$

where, c_b and k_b are damping and stiffness of ERBs system, respectively. The stiffness and damping of ERBs system are selected to provide the specific values of the two parameters namely the isolation time-period (T_b) and damping ratio (ξ_b) as

$$T_b = 2\pi \sqrt{\frac{M}{k_b}} \tag{3}$$

$$\xi_b = \frac{c_b}{2M\omega_b} \tag{4}$$

where, ($M = m_b + m_d$) is the total mass of the bridge deck; and $\omega_b = 2\pi/T_b$ is the isolation frequency.

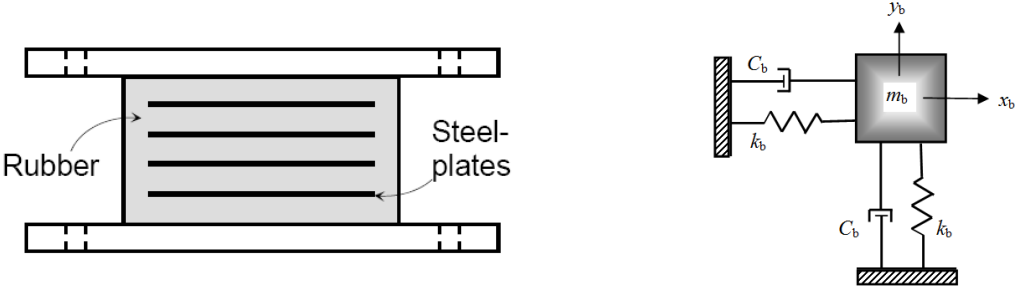


Fig. 3 a) Elastomeric Rubber Bearing and b) its schematic diagram

5. NUMERICAL STUDY

The seismic response of curved box girder bridge using ERBs is investigated for the four real earthquake ground excitation namely, El Centro (1940), Northridge (1994), Loma prieta (1989) and Kobe (1995) earthquakes. The important features of earthquake ground motion are shown in Table 2. For analysis east-west component of all earthquake are applied in chord direction, north-south component in radial direction of bridge. All the earthquakes are used at the full intensity for the evaluation of the performance of the proposed control strategy.

To facilitate direct comparison and to evaluate the ERBs system, a set of 10 evaluation criteria has been developed. The evaluation criteria J_1 - J_4 are defined to

Table 2. Earthquake Data for Numerical Simulation

Earthquake	Recording Station	Total Time (s)	PGA (g)		
			Vertical	N-S	E-W
El Centro (1940)	117 El Centro Array #9	40	0.205	0.313	0.215
Loma Prieta (1989)	16 LGPC	24.965	0.89	0.563	0.605
Northridge (1994)	24514 Sylmar – Olive View Med FF	40	0.535	0.834	0.604
Kobe (1995)	KJMA	48	0.343	0.821	0.599

measure the reduction in peak response quantities as peak base shear, peak overturning moment, peak mid-span displacement and peak mid-span acceleration of the curved box girder bridge. The evaluation criteria evaluated by normalizing the peak response quantities of controlled bridge by the corresponding peak response quantities for the uncontrolled bridge; J_6 - J_9 are based on the norm responses, calculated by normalizing the norm response quantities by the corresponding norm response of the uncontrolled bridge, and J_5 and J_{10} are related to the peak and norm displacement of bearing.

To investigate the robustness of the isolation systems on the seismic response of curved box girder bridge, the responses are obtained by varying important parameter of ERBs, as damping ratio (ξ_b), from 5 to 30% and considering isolation time period (T_b) equal to 2 sec. The variation of base shear, base moment, midspan displacement and midspan acceleration for different damping ratio of ERBs is shown in Figs. 4-7. It can be observed that, all responses are decreasing with increase in the damping ratio of the ERBs for all earthquakes; whereas vertical displacement and acceleration are remain constant for variation of damping ration. Hence, from the Figs. 4-7, it can be concluded that a higher amount of damping is beneficial in reducing the seismic responses of the curved box girder bridge. Further, for ξ_b equal to 15%, the T_b is varied from 1.25 sec to 3.5 sec. Figs. 8-11 show variation of different response quantities for different isolation time period. From Fig. 8 and 10 it is observed that the base shear response and overturning moment at pier base reduces with increasing time period of ERBs system. It is also observed that more reduction in base shear and overturning moment in chord direction compared to radial direction. From Figs. 9 and 11, it is observed that with increase in isolation time period mid span displacement get increase and mid span acceleration decreases slightly. Hence, lower value T_b is ideal for efficient displacement response, whereas higher T_b is preferred for better midspan acceleration response. Considering the value of the T_b as 2 sec and ξ_b equal to 15% for overall better response control for all earthquakes. Table 3 shows the values of different evaluation criteria for all earthquakes at ξ_b equal to 15% and T_b equal to 2 sec. The results of time history analyses along the chord and radial direction for reduction in base shear of pier 1 are presented in Fig. 12 under the Kobe (1995) earthquake. From the figure 12, it is observed that due to use of ERBs system huge amount of reduction in base shear of piers compared to uncontrolled structure.

In order to study the effect of curved geometry on the response of the isolation system, comparison between the responses of curved isolated bridge with straight isolated bridge is done. A straight isolated bridge modal with same cross section and material property as that of curved bridge, isolated with ERBs with parameter property ξ_b equal to 15% and T_b equal to 2 sec is made and time history analysis is carried out. From analysis result, peak displacement and norm displacement of isolation system obtain and compared with curved isolated bridge for different ground motions as shown in Table 4. From results, it is found that there is no significant difference in peak response in radial and chord direction.

Table 3. Evaluation criteria J_1 - J_4 and J_6 to J_9 for ERBs ($T_b=2$ Sec, $\xi_b=15\%$)

Peak Value	Location	Earthquake Direction	El Centro (1940)	Loma Prieta (1989)	Northridge (1994)	Kobe (1995)
J1	Pier 1	Chord	0.1665	0.0777	0.1348	0.0626
		Radial	0.0851	0.0821	0.0749	0.0452
	Pier 2	Chord	0.1504	0.1151	0.1667	0.0398
		Radial	0.0602	0.0955	0.0714	0.0431
J2	Pier 1	Chord	0.1806	0.0847	0.1431	0.0683
		Radial	0.0891	0.0833	0.0756	0.0474
	Pier 2	Chord	0.1597	0.1217	0.1821	0.0411
		Radial	0.0608	0.0979	0.0736	0.0440
J3	Deck	Chord	2.3355	1.5148	2.5044	0.6298
		Radial	3.8114	4.5419	3.4705	2.3478
		Vertical	1.9058	3.4884	0.9123	2.0852
J4	Deck	Chord	0.6026	0.7121	0.7293	0.4010
		Radial	0.5650	0.6086	0.4353	0.3910
		Vertical	0.5400	0.9144	0.5490	1.1526
J6	Pier 1	Chord	0.2023	0.0943	0.1995	0.0919
		Radial	0.0812	0.0936	0.0970	0.0574
	Pier 2	Chord	0.1814	0.1075	0.2180	0.0761
		Radial	0.0587	0.1151	0.1157	0.0428
J7	Pier 1	Chord	0.2189	0.0994	0.2107	0.0997
		Radial	0.0850	0.0956	0.0974	0.0598
	Pier 2	Chord	0.1939	0.1172	0.2370	0.0798
		Radial	0.0596	0.1184	0.1201	0.0432
J8	Deck	Chord	3.0496	1.3585	3.1963	1.0845
		Radial	3.4775	5.1537	5.2049	2.5731
		Vertical	1.9383	3.6024	1.8933	2.5224
J9	Deck	Chord	0.6258	0.4452	0.5786	0.4275
		Radial	0.4507	0.5741	0.4031	0.3988
		Vertical	0.8630	1.6283	0.8414	1.3543

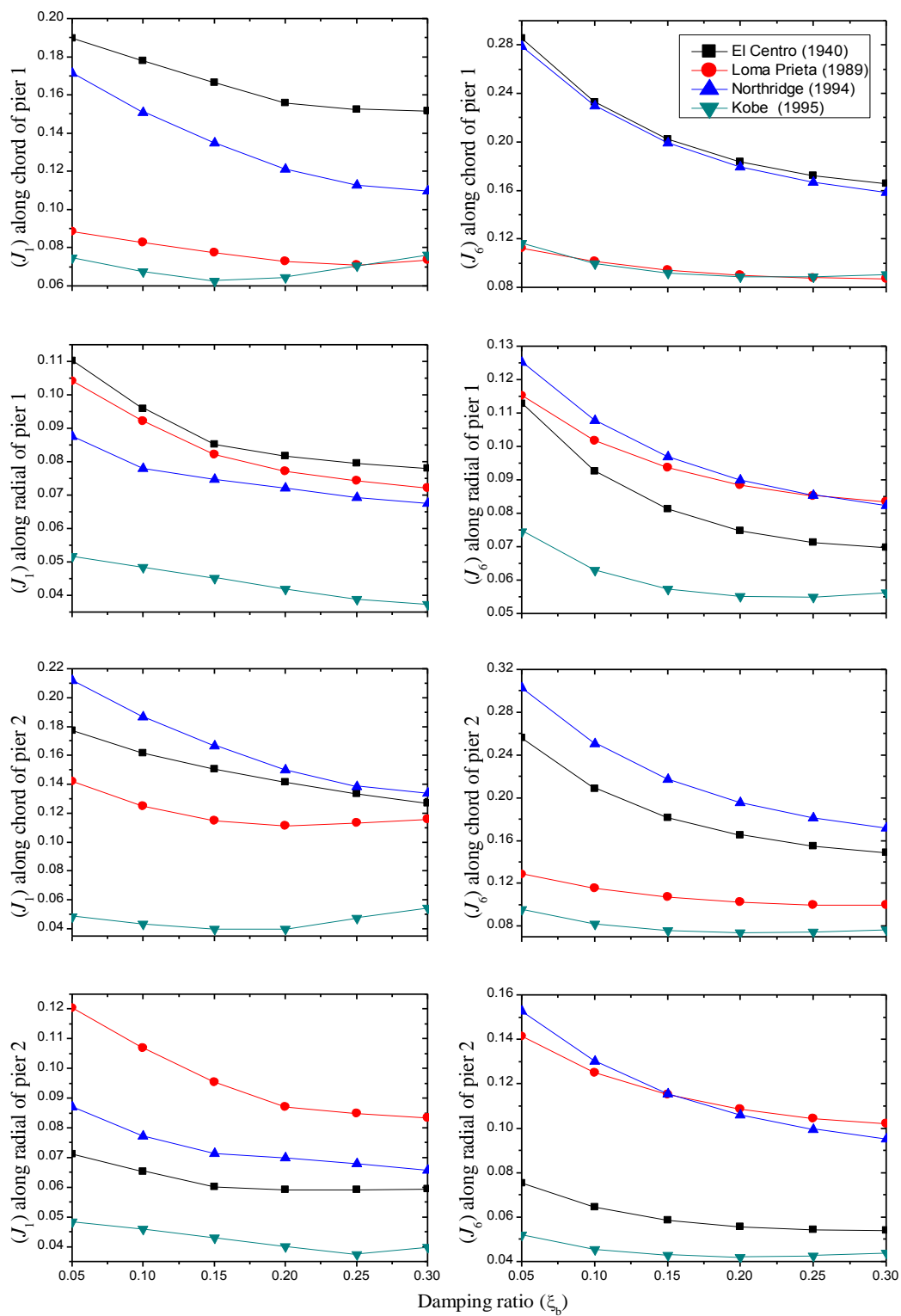


Fig.4 Effect of variation of damping ratio (ξ_b) on peak base shear (J_1) and norm base shear (J_6) for ERBs ($T_b = 2$ sec).

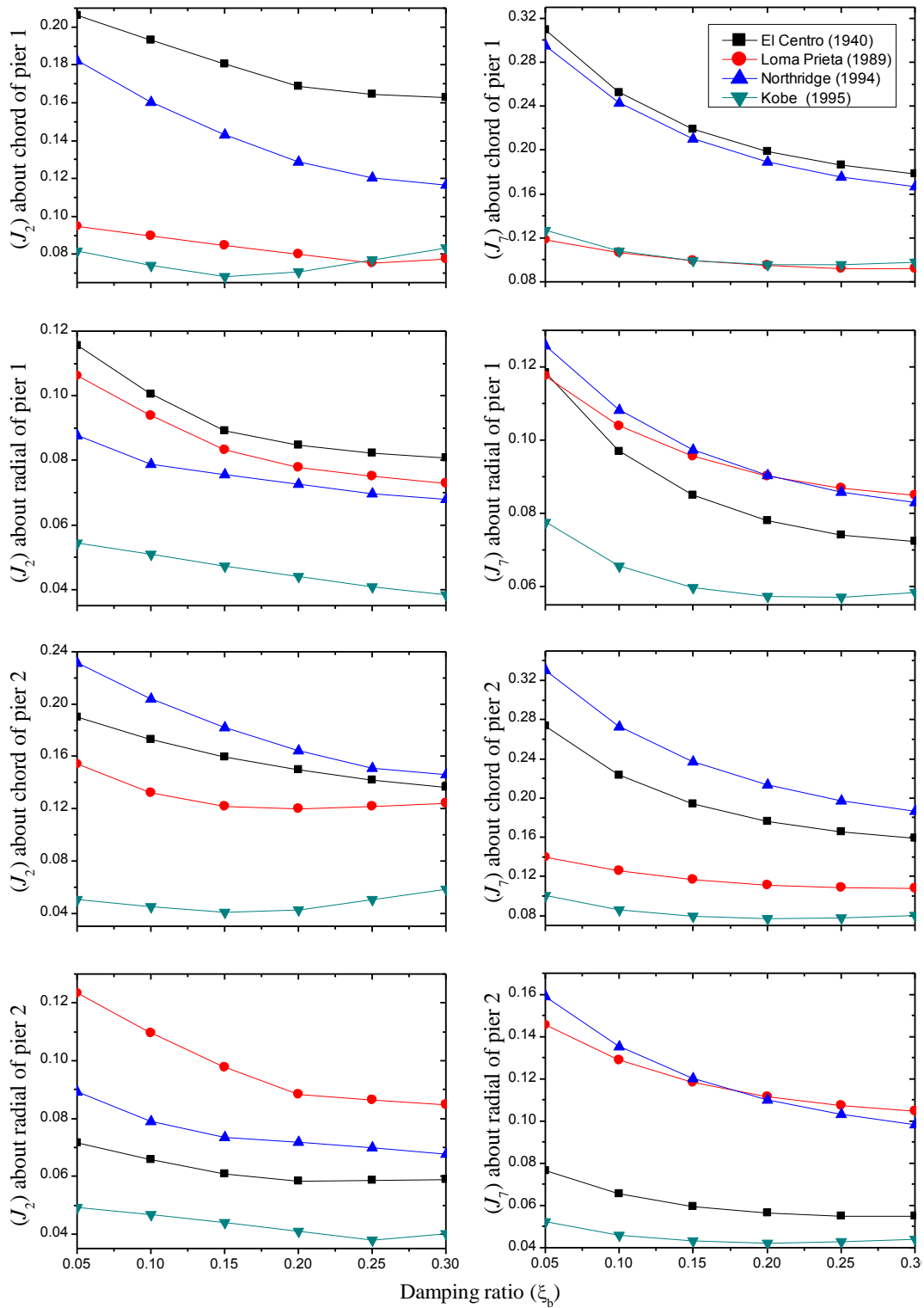


Fig.5 Effect of variation of damping ratio (ξ_b) on peak overturning moment (J_2) and norm overturning moment (J_7) for ERBs ($T_b = 2$ sec).

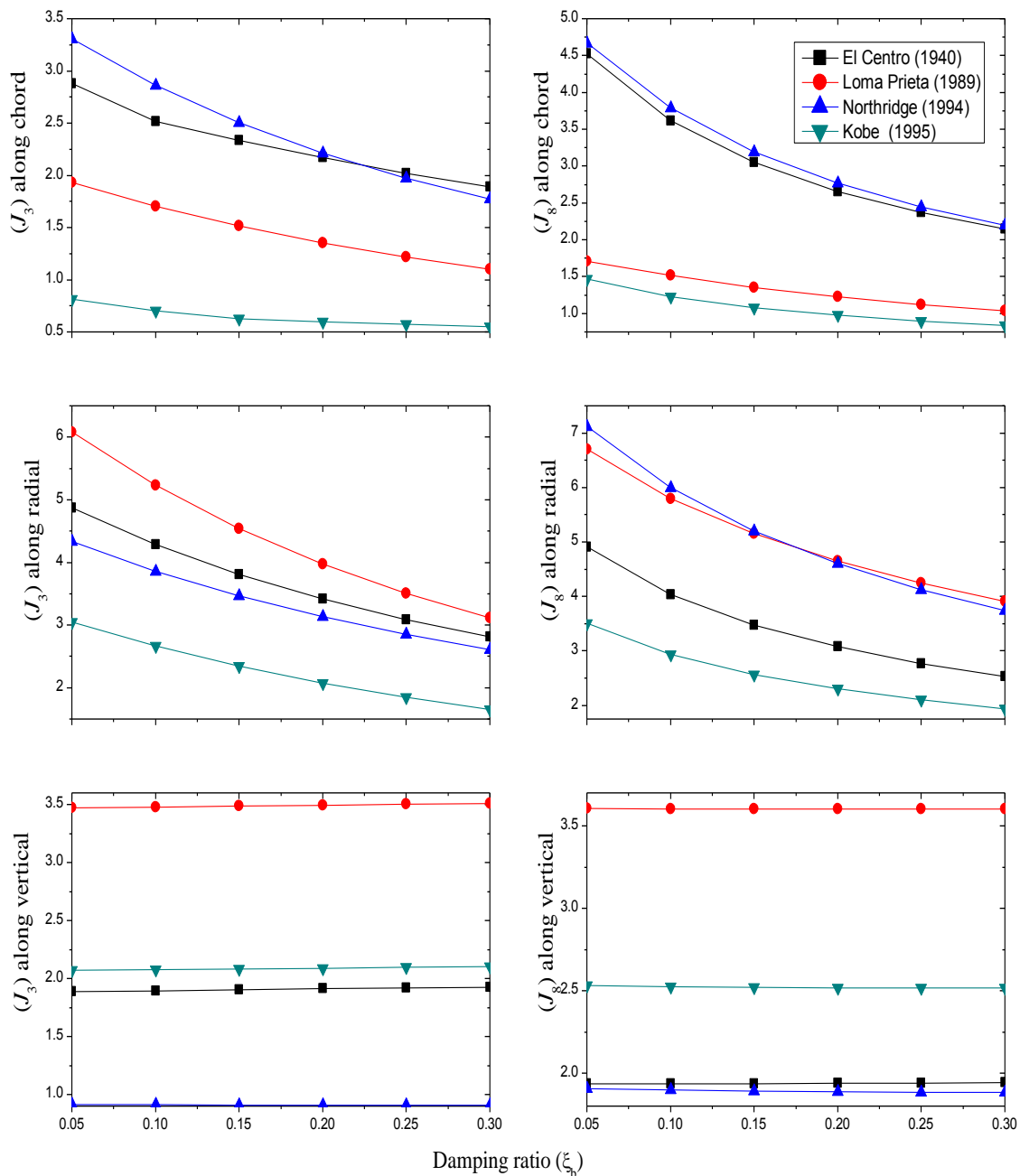


Fig.6 Effect of variation of damping ratio (ξ_b) on peak mid span displacement (J_3) and norm mid span displacement (J_8) for ERBs ($T_b = 2$ sec).

The results of time history analyses along the chord and radial direction of bearing 1 (left abutment top one bearing) for variation of displacement are plotted for straight and curved bridge in chord and radial direction as shown in Fig. 13. From figure, it is observed that displacement of bearing in radial direction in curved bridge is lesser than that of the straight one and the pattern of displacement of bearing is slightly changes in case of curved bridge compared to straight one.

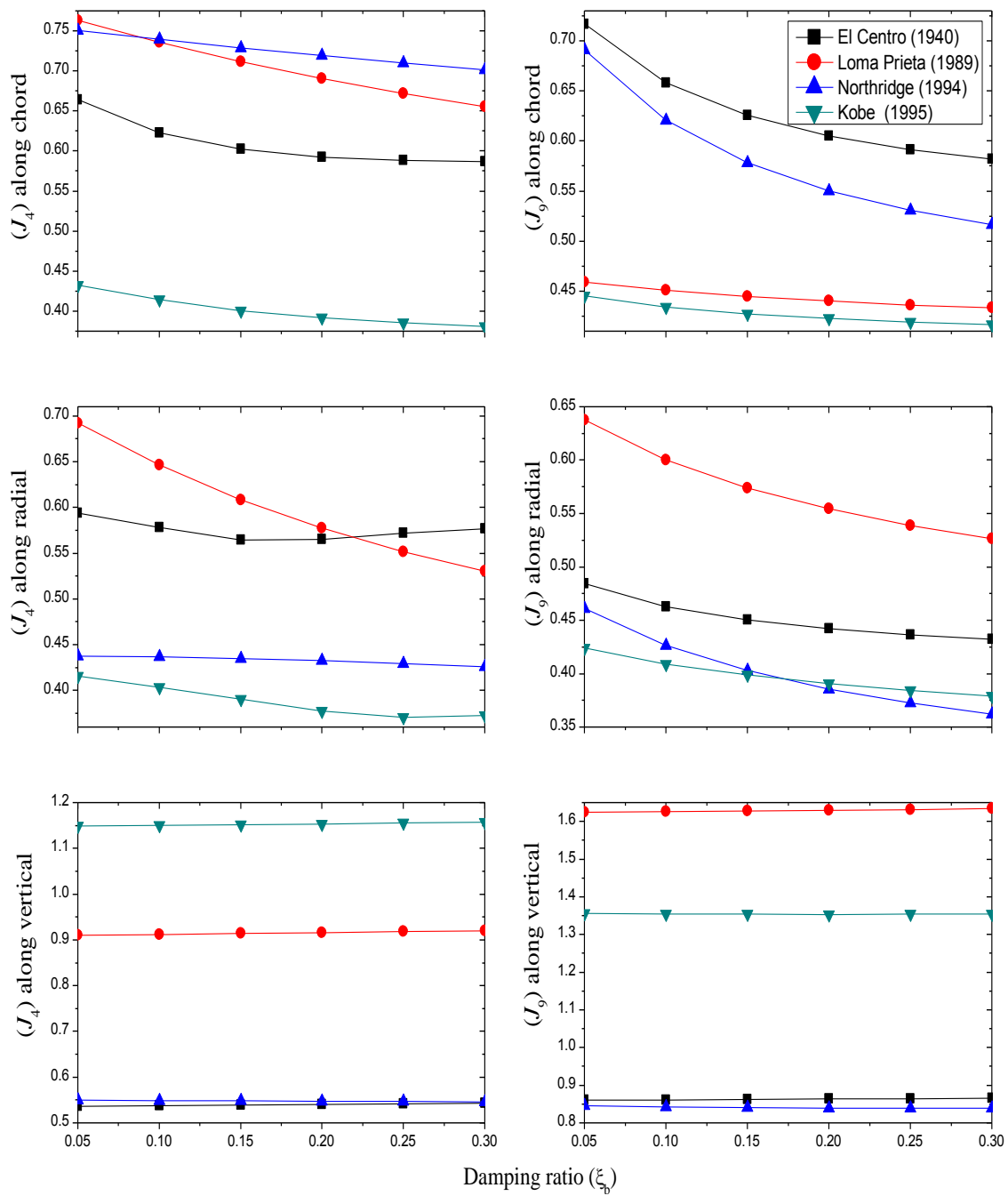


Fig.7 Effect of variation of damping ratio (ξ_b) on peak mid span acceleration (J_4) and norm mid span acceleration (J_9) for ERBs ($T_b = 2$ sec).

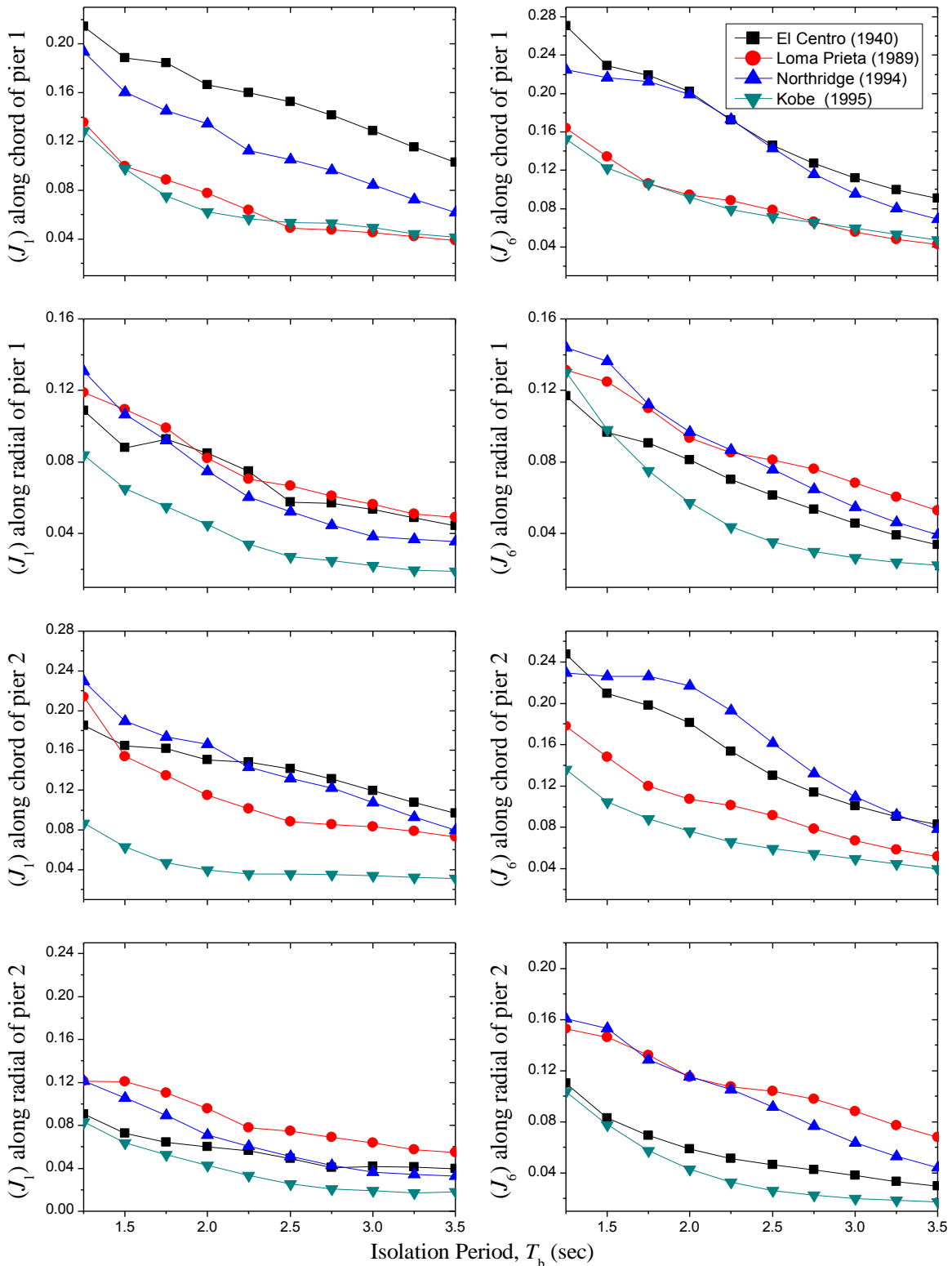


Fig.8 Effect of variation of isolation time period on peak base shear (J_1) and norm base shear (J_6) for ERBs ($\xi_b = 15\%$).

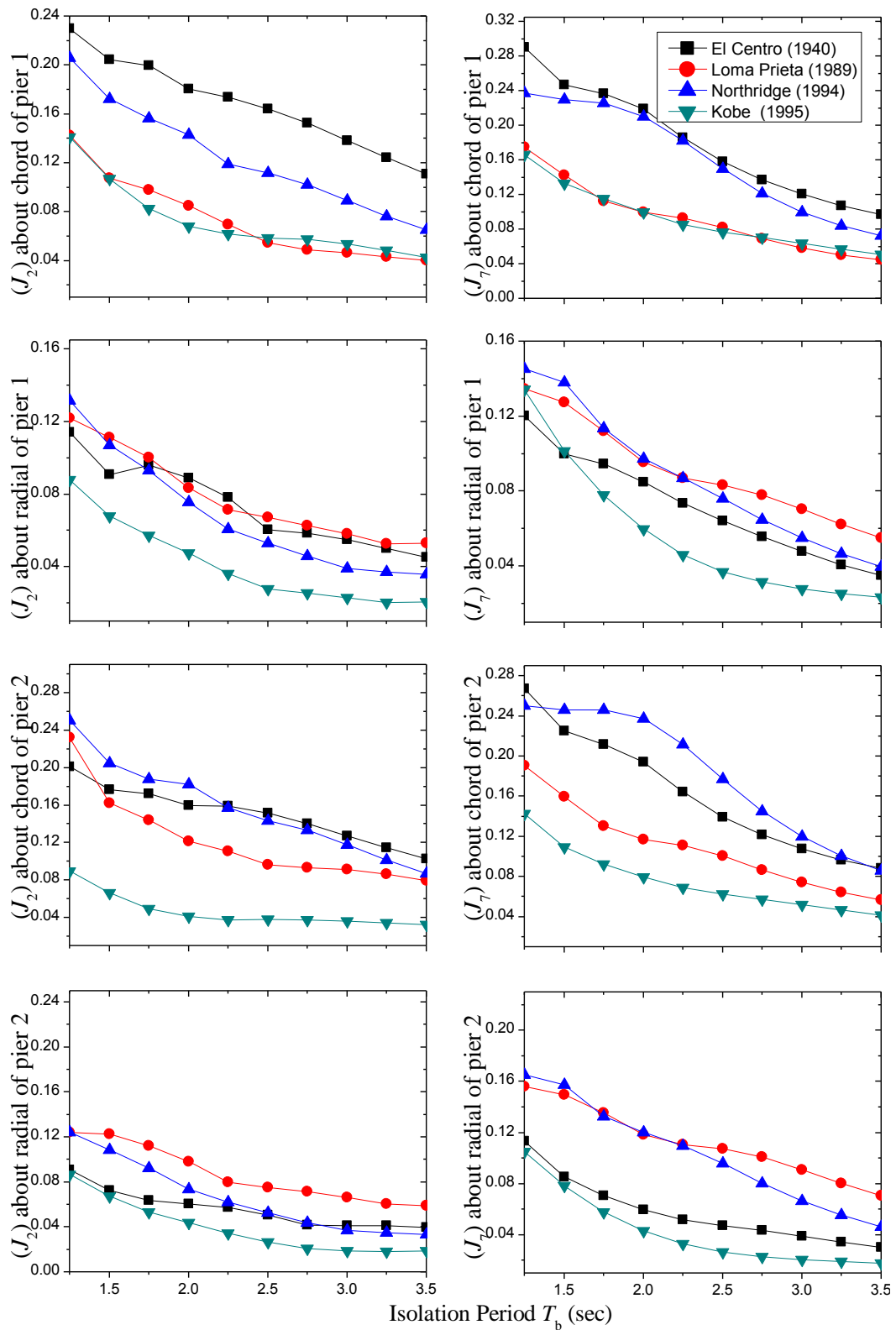


Fig.9 Effect of variation of isolation time period on peak overturning moment (J_2) and norm overturning moment (J_7) for ERBs ($\xi_b = 15\%$).

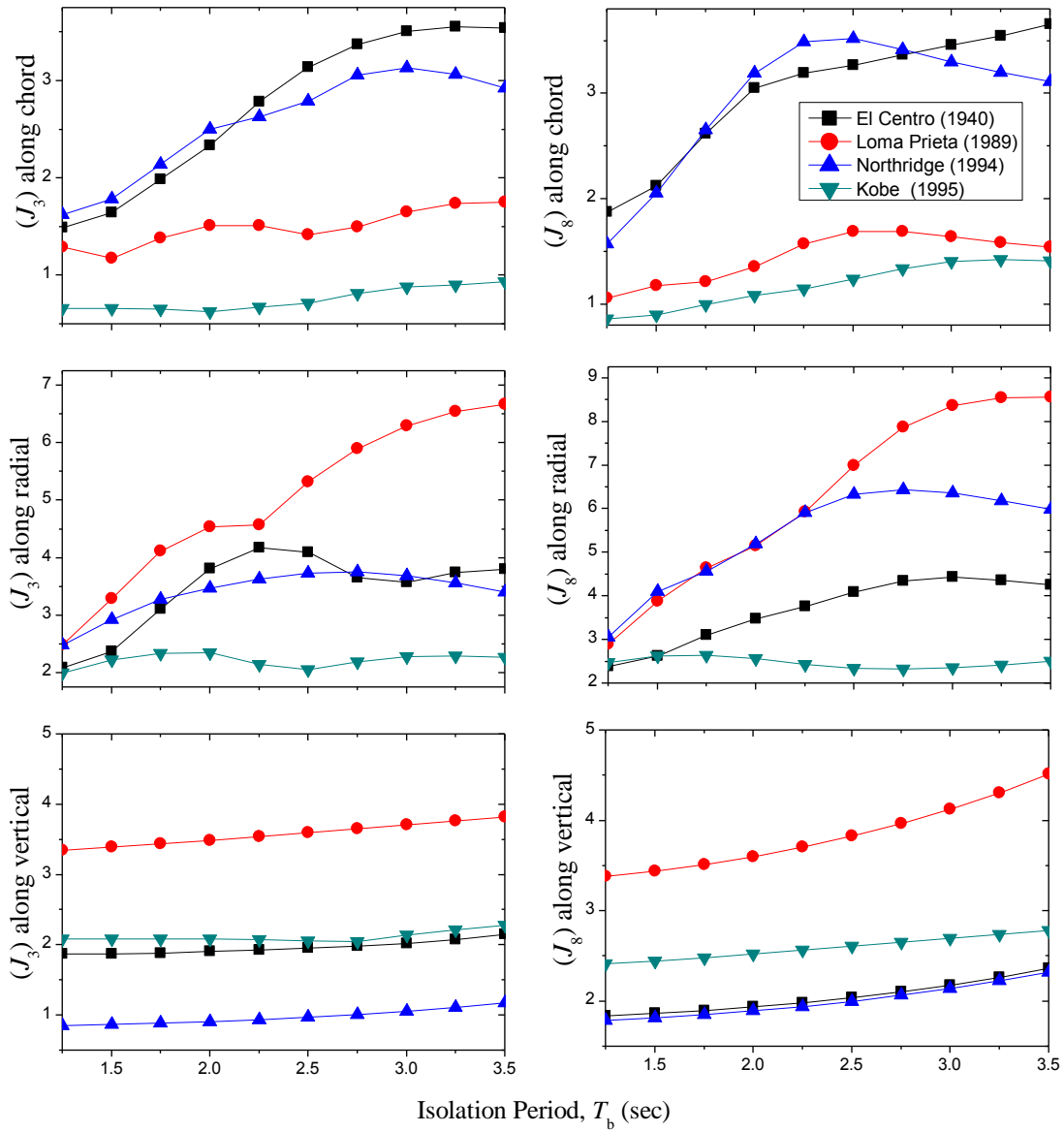


Fig. 10 Effect of variation of isolation time period on peak mid span displacement (J_3) and norm mid span displacement (J_8) for ERBs ($\xi_b = 15\%$).

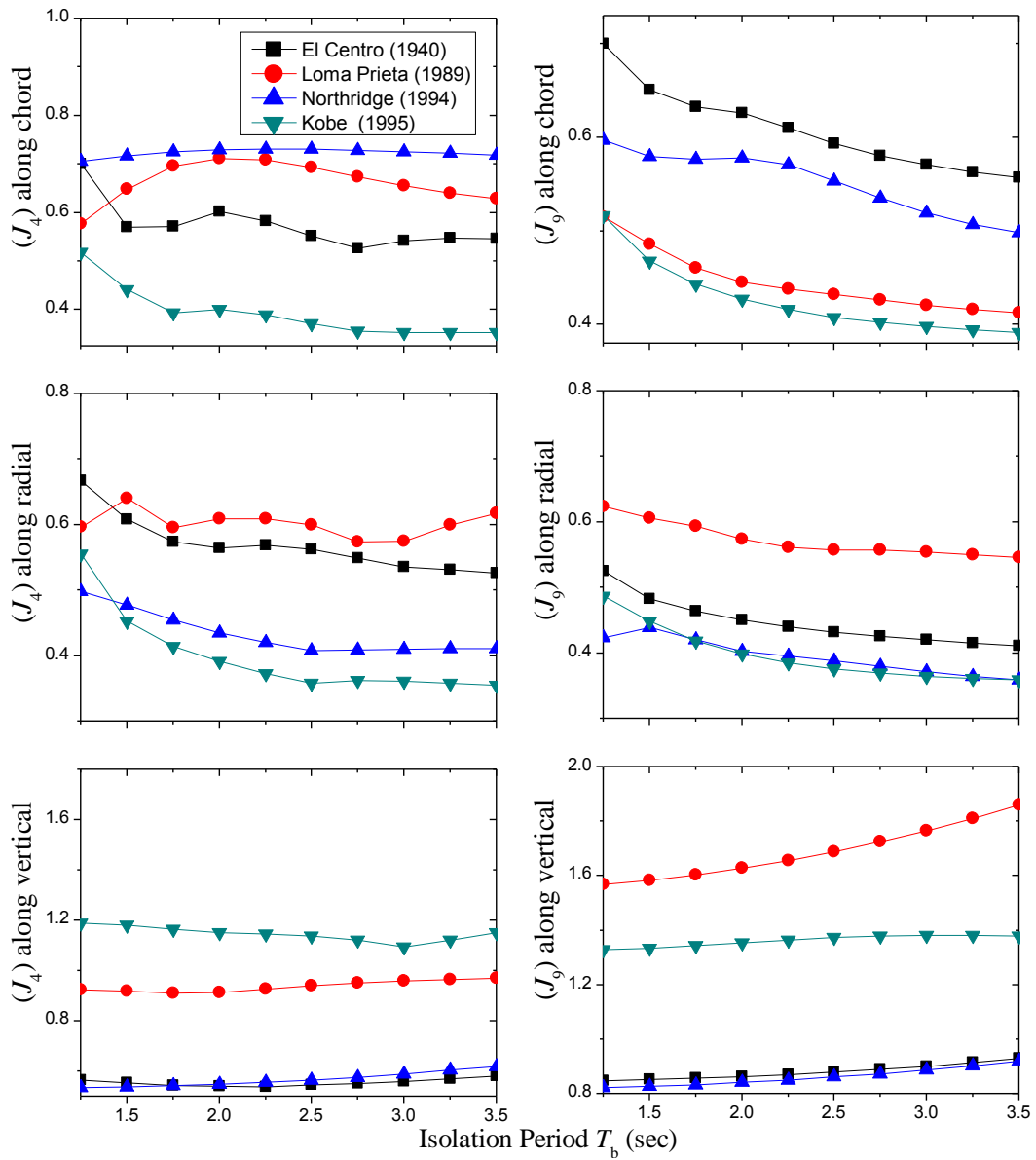


Fig. 11 Effect of variation of isolation time period on peak mid span acceleration (J_4) and norm mid span acceleration (J_9) for ERBs ($\xi_b = 15\%$).

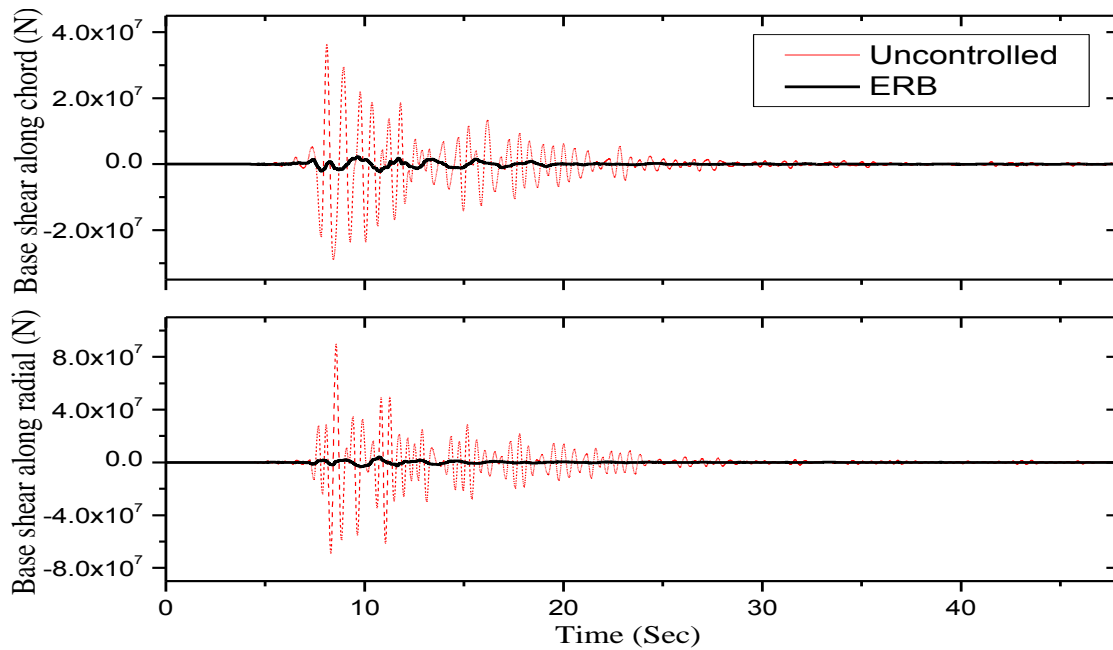


Fig. 12 Time variation of base shear of pier 1 along the chord and radial direction of bridge isolated with ERBs ($\xi_b = 15\%$ and $T_b = 2$ sec) under Kobe (1995) earthquake.

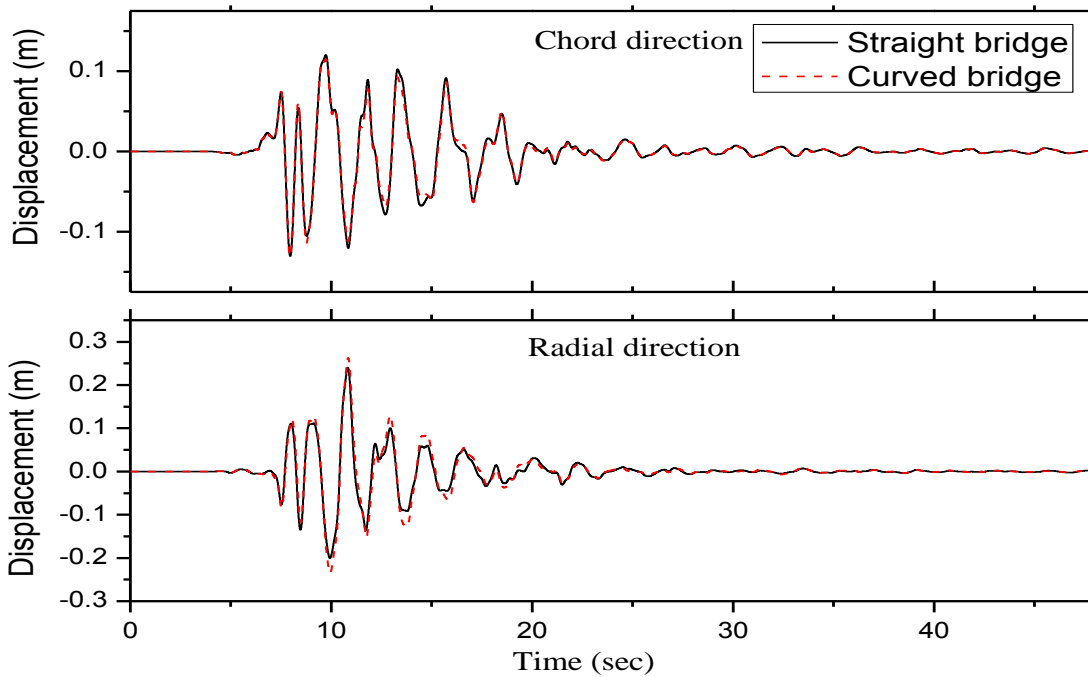


Fig. 13 Time variation of displacement of bearing along the chord and radial direction for straight and curved bridge isolated with ERBs ($\xi_b = 15\%$ and $T_b = 2$ sec) under Kobe (1995) earthquake.

Table 4. Peak displacement and norm displacement of bearings for straight and curved isolated bridge ($\xi_b = 15\%$ and $T_b = 2$ sec).

Peak displacement of bearings (J_5)									
Earthquake	Type of Bridge	Bearing 1		Bearing 2		Bearing 3		Bearing 4	
		Chord	Radial	Chord	Radial	Chord	Radial	Chord	Radial
El Centro (1940)	Curved	0.091	0.135	0.088	0.132	0.092	0.121	0.090	0.120
	Straight	0.093	0.114	0.094	0.114	0.091	0.112	0.091	0.112
Loma Prieta (1989)	Curved	0.140	0.350	0.133	0.355	0.134	0.364	0.136	0.366
	Straight	0.142	0.369	0.142	0.369	0.139	0.364	0.139	0.364
Northridge (1994)	Curved	0.245	0.342	0.236	0.348	0.249	0.363	0.241	0.365
	Straight	0.251	0.376	0.251	0.376	0.245	0.370	0.245	0.370
Kobe (1995)	Curved	0.130	0.262	0.131	0.260	0.119	0.246	0.122	0.245
	Straight	0.130	0.241	0.131	0.241	0.128	0.239	0.128	0.239
Norm displacement of bearings (J_{10})									
El Centro (1940)	Curved	0.025	0.026	0.024	0.025	0.026	0.023	0.025	0.023
	Straight	0.027	0.023	0.027	0.023	0.026	0.022	0.026	0.022
Loma Prieta (1989)	Curved	0.034	0.085	0.033	0.086	0.036	0.087	0.034	0.087
	Straight	0.035	0.089	0.035	0.089	0.034	0.087	0.034	0.087
Northridge (1994)	Curved	0.050	0.057	0.047	0.059	0.053	0.063	0.050	0.064
	Straight	0.052	0.067	0.052	0.067	0.051	0.066	0.051	0.066
Kobe (1995)	Curved	0.028	0.045	0.028	0.044	0.028	0.041	0.028	0.041
	Straight	0.030	0.040	0.030	0.040	0.029	0.040	0.029	0.040

6. CONCLUSION

The analytical seismic response of a horizontally curved concrete box girder bridge isolated by ERBs is investigated. The seismic response of the bridge with ERBs is evaluated using standard numerical technique under two horizontal and one vertical component of the four different earthquake ground motions. The effectiveness of the ERBs studied under different system parameters for assessment of its performance. From the trend of the results of the present study, the following conclusions are drawn:

1. With the installation of ERBs in the horizontally curved concrete box girder bridge the base shear and overturning moment under different ground motions can be controlled within a desirable range,

2. All responses J_1 to J_4 are decreasing with increase in the damping ratio of the ERBs for all considered earthquake ground motions,
3. The effect of curved geometry makes no significant difference in peak response mainly peak isolator displacements of ERBs system where as pattern of displacement in radial and chord direction changes slightly and
4. The ERBs found to be effective for controlling the seismic response of curved bridge.

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